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Empirical algorithms to restore a complete set of inherent optical properties of seawater

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ABSTRACT

This work analyzes available experimental and in situ information obtained by different investigators and presents it in the form of simple usable algorithms and codes. The following independent algorithms are presented: 1) the retrieval of backscattering coefficient through the measurements of beam attenuation and beam scattering coefficients, 2) the retrieval of angular scattering coefficient through the measurements of beam attenuation and absorption coefficients, 3) the retrieval of downward and upward mean cosines in the depth regime through the Gordon's parameter that depends on backscattering and absorption coefficient, 4) the retrieval of diffuse attenuation and diffuse reflection coefficients through the Gordon's parameter. The applicability of these algorithms is discussed and examples of their applications are presented.

Keywords: Ocean optics, inherent optical properties, scattering, absorption, seawater.

1.0 INTRODUCTION

A complete set of inherent optical properties of the seawater includes a beam attenuation and an angular scattering coefficients. Due to financial and/or technological limitations majority of *in situ* optical experiments does not include a complete set of hydrooptical measurements. To use these experimental data to enhance sea water optical models and calibrate atmospheric correction algorithms it is necessary to have some means to estimate the absent inherent optical properties through the measured ones.

The algorithms presented here allow us to predict all inherent optical properties, including angular scattering coefficient $\beta(\theta)$ (here θ is a scattering angle), from the values of any two pair of the following optical properties: scattering coefficient b, absorption coefficient a, beam attenuation coefficient $c = a + b$, and single scattering albedo $\omega_0 = b / c$. These algorithms are based on an expereimental data and does not include spectral dependence on wavelength. The algorithm to restore spectral inherent optical properties may be found in another paper published in these proceedings (Haltrin, 1999b).

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2.0 ALGORITHM TO RETRIVE DOWNWARD AND UPWARD MEAN COSINES

Theoretically average cosine over radiance distribution in the depth of scattering media, and downward and upward cosines over the same distribution, depend on two optical properties: single-scattering albedo $\omega_0 = b / c$ and phase function of scattering $p(\cos\theta)$ (see Zege, Ivanov and Katsev, 1991; Haltrin, 1997a and 1997b, Haltrin, Kattawar and Weidemann, 1997; Haltrin 1998). But under natural maritime conditions some kind of biological equilibrium is usually established. This equilibrium explains significant correlation between inherent optical properties (Timofeyeva, 1971a and 1971b; Petzold, 1972; Efimenko and Pelevin, 1975; Haltrin, 1985; Aas, Højerslev, and Lundgren, 1997; and Haltrin, 1998a). Based on analysis of experimental data Haltrin (1997b) proposed the following regression between average cosine $\bar{\mu}$ and single scattering albedo:

$$\bar{\mu} = \sqrt{1-\omega_0}\sum_{n=0}^{6} c_n \left(1-\omega_0\right)^{\frac{n}{2}} \equiv \sqrt{1-\frac{b}{c}}\sum_{n=0}^{6} c_n \left(1-\frac{b}{c}\right)^{\frac{n}{2}}. \tag{1}$$

Connections between downward and upward average cosines (μ_d and μ_u) and average cosine $\bar{\mu}$ were proposed earlier in the paper by Haltrin and Weidemann (1996). These empirical relationships represent the experimental data collected by Timofeyeva (1971-1979) and other investigators, and they have the following analytic form:

$$\mu_d = \frac{1-\bar{\mu}(1-\bar{\mu})^2 \sum_{n=0}^{3} d_n \bar{\mu}^{2n}}{2-\bar{\mu}}, \tag{2}$$

$$\mu_u = \frac{1-\bar{\mu}(1-\bar{\mu})^2 \exp\left(\sum_{n=0}^{4} u_n \bar{\mu}^{2n}\right)}{2-\bar{\mu}}. \tag{3}$$

The coefficients c_n, d_n, and u_n in Eqs. (1)-(3) are given in Table 1.

Table 1. Coefficients to Eqs. (1)-(3).

n	c_n	d_n	u_n
0	2.6178398	0.0326	-0.0131
1	-4.6024180	0.1661	8.4423
2	9.0040600	0.7785	-15.6605
3	-14.59994	0.0228	21.8820
4	14.83909		-11.2257
5	-8.117954		
6	1.8593222		

Equations (1)-(3) express all three average cosines through the value of a single scattering albedo. These relationships within 10% of accuracy coincide with the independently developed one-parameter model of seawater optical properties (see Haltrin, 1998b and 1999b).

3.0 ALGORITHM TO RETRIVE BACKSCATTERING COEFFICIENT

Remote sensing reflectance and other optical properties of the seawater may be optained from two basic optical properties: absorption coefficient a and backscattering coefficient b_B (Haltrin, 1984; Gordon, Brown and Jackobs, 1975; Gordon, 1993).

The relationship between backscattering coefficient and absorption and beam attenuation may be obtained from the following chain of equations: 1) reversal of the Gordon's parameter definition, $g = b_B / (a + b_B)$:

$$b_B = \frac{g\,a}{1-g} \equiv \frac{g(c-b)}{1-g}, \tag{4}$$

2) dependence of Gordon's parameter g on average cosine $\bar{\mu}$ (Haltrin and Kattawar, 1993; Haltrin, 1998a):

$$g = \frac{(1-\bar{\mu}^2)^2}{1+\bar{\mu}^2(4-\bar{\mu}^2)}, \tag{5}$$

3) Equation (1) that connects average cosine with absorption and attenuation coefficients.

4.0 ALGORITHM TO RETRIVE DIFFUSE REFLECTION AND DIFFUSE ATTENUATION COEFFICIENTS

The diffuse reflection R coefficient is determined through the well-known relationship:

$$R = \frac{1-\bar{\mu}/\bar{\mu}_d}{1+\bar{\mu}/\bar{\mu}_u} \equiv \frac{\bar{\mu}_u}{\bar{\mu}_d}\cdot\frac{\bar{\mu}_d-\bar{\mu}}{\bar{\mu}_u+\bar{\mu}}, \tag{6}$$

which connects R with average cosines $\bar{\mu}$, $\bar{\mu}_d$ and $\bar{\mu}_u$ (Eqs. (1)-(3)). Equation (6) may be easily derived by integrating a radiative transfer equation (Haltrin, 1984; Zege, Ivanov and Katsev, 1991).

The asymptotic diffuse attenuation coefficient k_∞ is determined through the Gershun's equation, $k_\infty = a/\bar{\mu}$, or, after a substitution of Eq. (1):

$$k_\infty = \sqrt{c^2 - bc}\Big/\sum_{n=0}^{6} c_n [1-(b/c)]^{\frac{n}{2}}. \tag{7}$$

The downward and upward depth dependent diffuse attenuation coefficients under arbitrary surface illumination may be determined by Eqs. (42) and (43) in Haltrin (1998b).

5.0 ALGORITHM TO RETRIVE SEAWATER LIGHT SCATTERING PHASE FUNCTION

Empirical representation of angular scattering coefficient $\beta(\theta)$ and of the scattering phase function $p(\theta)$ based on experimental data by Petzold (1972) is derived in Haltrin, (1997b):

$$\beta(\theta) = \exp\left[q \sum_{n=0}^{5} k_n \, \theta^{\frac{n}{2}} \right], \tag{8}$$

$$p(\theta) = \frac{4\pi}{b} \exp\left[q \sum_{n=0}^{5} k_n \, \theta^{\frac{n}{2}} \right], \tag{9}$$

$$\frac{1}{2} \int_0^{\pi} p(\theta) \sin\theta \, d\theta = 1, \tag{10}$$

here θ is the scattering angle in degrees and coefficients q and k_n $(n = 0, 5)$ are represented by the following equations:

$$q = 2.598 + 17.748\sqrt{b} - 16.722\,b + 5.932\,b\sqrt{b}\ , \tag{11}$$

$$\left. \begin{array}{lll} k_0 = 1, & k_2 = 0.307 - 0.19\,\omega_0\,, & k_4 = 10^{-3}\left(3.24 - 2.25\,\omega_0\right), \\ k_1 = 0.688\,\omega_0 - 1.188, & k_3 = 0.0302\,\omega_0 - 0.0458, & k_5 = 10^{-4}\left(0.61\,\omega_0 - 0.84\right). \end{array} \right\} \tag{12}$$

The regressions given by Eqns. (8)-(12) can be used as a basis for an empirical model of the seawater phase function with the coefficients dependent on the absorption and scattering coefficients. The single-scattering albedo used here varies from 0.09 to 0.96.

6.0 CONCLUSION

The set of equations (1)-(12) presented here allow us to calculate the whole set of inherent optical properties from two input parameters: absorption coefficient b and beam scattering coefficient c. This model is compared with independently derived one-parameter model of sea optical properties (Haltrin, 1998c; Haltrin, 1999). The predictions of this model coincide with the predictions of the one-parameter model with the error about 10%. The full working FORTRAN code of ths model is given in the APPENDIX of this paper. The output of this code includes backscattering coefficient b_B, probability of backscattering B, all average cosines, diffuse and attenuation coefficients, and a phase function of scattering. The results of a sample output are shown in Fig.1.

7.0 ACKNOWLEDGMENT

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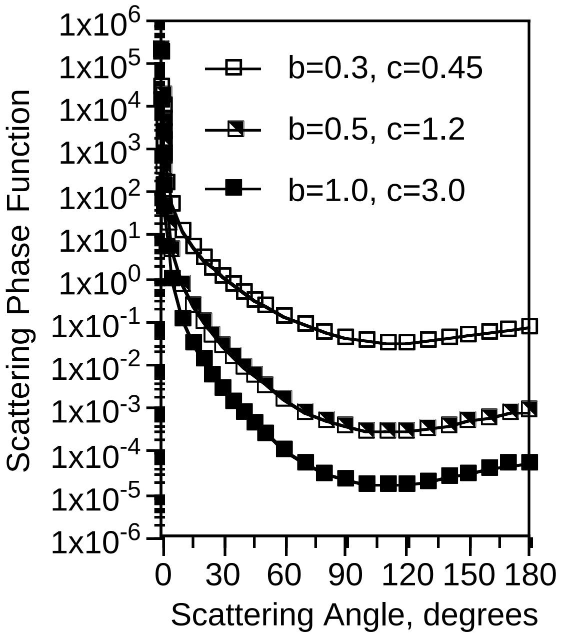

Fig. 1. Examples of output Phase Functions

Table 2. Results of three sample runs of the program `fiopexp`.

Input:			
b	0.30	0.5	1.0
c	0.45	1.2	3.0
Output:			
a	0.15	0.70	2.0
b_B	0.007990	0.009431	0.016091
B	0.026633	0.018862	0.016091
$\overline{\mu}$	0.778909	0.885248	0.910921
$\overline{\mu}_d$	0.805688	0.890244	0.913432
$\overline{\mu}_u$	0.350256	0.618432	0.721439
g	0.050572	0.013294	0.007981
R	0.010310	0.002308	0.001215
k_∞	0.192577	0.790739	2.195581

APPENDIX: A PROGRAM TO CALCULATE ALL INHERENT OPTICAL PROPERTIES THROUGH A SCATTERING AND A BEAM ATTENUATION COEFFICIENT

```
!  program fiopexp; written by Vladimir I. Haltrin, <haltrin@nrlssc.navy.mil>
!  this program is free for any non-commercial use
!  a reference to this article is required
      implicit   none
      integer    i,Nang,Nan
      parameter  (Nang = 361)
      real*8     b,c,a,g,bB,Bbk,R,mu,mud,muu,kdf
      real*8     ang(Nang),phf(Nang)
      character  tb
      logical    badinput

      open(11, file='fiopexp.in', status='old')
         read(11,*) b
         read(11,*) c
         read(11,*) Nan                           ! Nan < Nang
         read(11,*) (ang(i), i=1,Nan)
      close(11)

      if ((c.le.0.).or.(b.lt.0.).or.(c.lt.b)) then
         badinput = .true.
      else
         badinput = .false.
         call siopexp(b,c,  a,bB,Bbk,mu,mud,muu,g,R,kdf)
         call sphf(b,c,Nan,ang, phf)
      end if
      tb = CHAR(9)
```

```
      open(21, file='fiopexp.out', status='new')
      if (badinput) then
         write(21,'(a)') 'bad input in "fiopexp.in"'
      else
      write(21,30) 'Input:       Scattering coefficient, b = ',b
     &                                                        , ' 1/m'
      write(21,30) 'Input:       Attenuation coefficient, c = ',c
     &                                                        , ' 1/m'
      write(21,*)
      write(21,'(a7)') 'Output:'
      write(21,30) 'Computed absorption coefficient, a = ',a,' 1/m'
      write(21,30) 'Computed backscattering coefficient, bB = ',bB
     &              ,' 1/m'
      write(21,30) 'Computed backscattering probability, B = ',bBk
      write(21,30) 'Computed average cosine <mu> = ',mu
      write(21,30) 'Computed downward average cosine <mud> = ',mud
      write(21,30)   'Computed upward average cosine <muu> = ',muu
      write(21,30) "Computed Gordon's parameter g = ",g
      write(21,30) 'Computed diffuse reflectance coefficient, R = ',R
      write(21,30) 'Computed diffuse attenuation coefficient, k = '
     &                                                           ,kdf
         open(22,file='phf.out', status='new')
            write(22,40) 'ang, °',tb,'phfunc'
            do i=1,Nan
                write(22,50) ang(i),tb,phf(i)
            end do
         close(22)
      end if
      close(21)

  30  format(a42, f10.6,a7)
  40  format(a6,a1,a6)
  50  format(f6.2,a1,g12.5)

      end

      subroutine sphf(b,c,Nan,ang, phf)
      implicit  none
      integer   i,Nan
      real*8    b,c,ang(Nan),phf(Nan)
      real*8    q,omg,p,sqa,sqb,k1,k2,k3,k4,k5
      sqb = SQRT(b)
      omg = b/c
      q = 2.598+sqb*(17.748+sqb*(5.932*sqb-16.722))
      do i=1,Nan
         sqa = SQRT(ang(i))
         k1 = 0.688*omg - 1.188
         k2 = 0.307 - 0.19*omg
         k3 = 0.0302*omg - 0.0458
         k4 = (3.24 - 2.25*omg)*1.e-3
         k5 = (0.61*omg - 0.84)*1.e-4
         p = 1.+sqa*(k1+sqa*(k2+sqa*(k3+sqa*(k4+k5*sqa))))
         phf(i) = (12.56637062/b)*EXP(q*p)
      end do
      return
      end
```

```
      subroutine siopexp(b,c,  a,bB,Bbk,mu,mud,muu,g,r,kdf)
      implicit  none
      real*8    b,c,  a,bB,Bbk,mu,mud,muu,g,r,kdf
      real*8    fmuav,fgord
      a = c-b
      mu = fmuav(b,c)
      g  = fgord(mu)
      bB = g*a/(1.-g)
      Bbk = bB/b
      call fsememp(mu, mud,muu,r)
      kdf = a/mu
      return
      end

      real*8 function fmuav(b,c)
      implicit   none
      real*8     b,c,y
      y = SQRT(1.-b/c)
      fmuav = y*(2.6178398+y*(-4.6024180+y*(9.0040600+
     &        y*(-14.59994+y*(14.83909+y*(-8.117954+1.8593222*y))))))
      return
      end

      real*8 function fgord(mu)
      implicit   none
      real*8     mu,m2,g
      m2 = mu*mu
      g  = (1.-m2)
      fgord = g*g/(1.+m2*(4.-m2))
      return
      end

      subroutine fsememp(mu, mud,muu,R)
      implicit  none
      real*8    mu,mud,muu,R,m2,d,z
      m2 = mu*mu
      d = 1.-mu-mu+m2
      z = 1./(2.-mu)
      mud = (1.-mu*d*(0.0326+m2*(0.1661+m2*(0.7785+0.0228*m2))))*z
      muu = (1.-mu*d*exp(-.0131+m2*(8.4423+m2*(-15.6605
     &    + m2*(21.882-11.2257*m2))))))*z
      R = (1.-mu/mud)/(1.+mu/muu)
      return
      end
```

Input file “fiopexp.in”:

```
0.3         <-- scattering coefficient b in 1/m (0 < b <= c)
0.45        <-- beam attenuation coefficient c in 1/m
30    <-- Nan, a number of angles for phase function (in degrees); ang(Nan):
0.    0.1   0.3   0.5   1.    1.5   3.0   5.    10    15.
20.   25.   30.   35.   40.   45.   50.   60.   70.   80.
90.         100.  110.  120.  130.  140.  150.  160.  170.  180.
```

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